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Short communication

The GDI-Kinetic: A new index for quantifying kinetic deviations from normal gait

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ABSTRACT

This article introduces a new index, the GDI-Kinetic; a direct analog of the GDI based on joint kinetics rather than kinematics. The method consists of: (1) identifying "features" of the raw gait kinetic data using singular value decomposition, (2) identifying a subset of features that account for a large percentage of the information in the raw gait kinetic data, (3) expressing the raw data from a group of typically developing children as a linear combination of these features, (4) expressing a subject's raw data as a linear combination of these features, (5) calculating the magnitude of the difference between the *subject* and the mean of the *control*, and (6) scaling and transforming the difference, in order to provide a simple, and statistically well-behaved, measure. Linear combinations of the first 20 gait features produced a 91% faithful reconstruction of the data. Concurrent and face validity for the GDI-Kinetic are presented through comparisons with the GDI, Gillette Functional Assessment Questionnaire Walking Scale (FAQ), and topographic classifications within the diagnosis of Cerebral Palsy (CP). The GDI-Kinetic and GDI are linearly related but not strongly correlated ($r^2 = 0.24$). Like the GDI, the GDI-Kinetic scales with FAQ level, distinguishes levels from one another, and is normally distributed across FAQ levels six to ten, and among typically developing children. The GDI-Kinetic also scales with respect to clinical involvement based on topographic CP classification in Hemiplegia types I–IV, Diplegia, Triplegia, and Quadriplegia. The GDI-Kinetic complements the GDI in order to give a more comprehensive measure of gait pathology.

1. Introduction

There is a need for, and interest in, methods to quantify the amount of pathology present in the gait of patients. The needs range from gait classification to objective assessment of outcome. The interest can be seen in the number of techniques that have been proposed [1–4]. Recently, the gait deviation index (GDI) was introduced as a measure of overall gait pathology [5]. The GDI is an intuitively scaled distance between the kinematics of a pathological gait pattern and those of the average normal gait pattern; based on a reduced-order approximation of the gait cycle. The GDI has been shown to be valid, robust, and practical [6–8]. The method used to derive the GDI can be applied to a broad range of waveform signals, including gait kinetics.

The following study introduces a new index, the GDI-Kinetic; a direct analog of the GDI; based on joint kinetics rather than kinematics.

2. Methods

The methodology used to develop the GDI was applied to kinetic variables to calculate the GDI-Kinetic [5]. Briefly, the method consists of:

1. Identifying "features" of the raw gait kinetic data using singular value decomposition. This step is described in detail below.
2. Identifying a subset of features that account for a large percentage of the information in the raw gait kinetic data.
3. Expressing the raw data from a group of typically developing children as a linear combination of the features chosen in step 2 (*control feature scores*).
4. Expressing a subject's raw data as a linear combination of the features chosen in step 2 (*subject feature scores*).
5. Calculating the magnitude of the difference between the *subject feature scores* and the mean of the *control feature scores*.
6. Scaling and transforming the difference found in the step 5, in order to provide a simple, and statistically well-behaved, measure.

The data used to identify the features in steps 1 and 2 were compiled from subjects seen in our center between February 1994 and January 2010, who completed gait trials without the use of assistive devices. In each session, for each side, barefoot strides that included a clean force plate strike were averaged. This resulted in at most two strides per session for each subject, for a total of $N_{strides} = 8488$ strides from 2792 subjects (some subjects were evaluated during multiple sessions). All data had been processed using either the Vicon Clinical Manager or Plug-in-Gait model. There was no explicit filtering of the kinetics. However, cubic splines were fit to the marker trajectories which facilitates algebraic differentiation of the spatial data over time. This results in smoother kinetics than if

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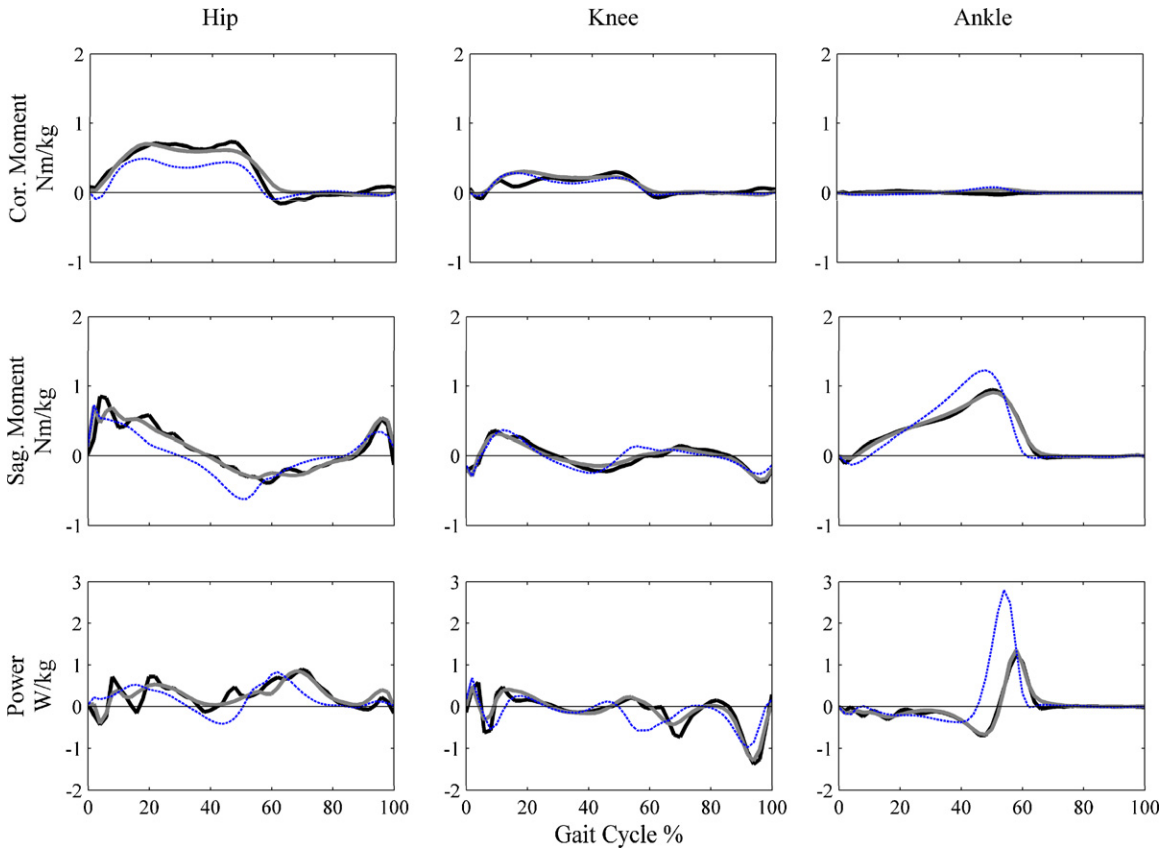

Fig. 1. Moment and power graphs from one subject with GDI-Kinetic = 86. Black solid (): original data, grey solid (): reconstructed data, blue dotted (): average normal kinetics. The reduced-order approximation faithfully reproduces most of the important elements of the kinetics (peaks, timing, ranges). Some filtering affects can be seen (*e.g.* in the Hip Power graph). These may be desirable, as in the case of noisy data, or undesirable, as in the case of rarely arising kinetic deviations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

numerical differentiation of the raw data was used and essentially acts as a low-pass filter. Coronal and sagittal plane moments, and total joint power at the hip, knee, and ankle were normalized to body mass. The moments and powers were extracted at 2% increments throughout the gait cycle (6 moments × 51 points + 3 powers × 51 points = 459 datum). The data were then arranged in 459 × 1 gait vectors ($\mathbf{k}^i$, $i = 1, N_{strides}$).

$$\mathbf{k} = \begin{bmatrix} \{\text{sagittal hip moment}\}, \{\text{coronal hip moment}\}, \\ \{\text{sagittal knee moment}\}, \{\text{coronal knee moment}\}, \\ \{\text{sagittal ankle moment}\}, \{\text{coronal ankle moment}\}, \\ \{\text{hip power}\}, \{\text{knee power}\}, \{\text{ankle power}\} \end{bmatrix}^T \quad (1)$$

$$\mathbf{k} = [\{k_{1-51}\}, \{k_{52-102}\}, \ldots, \{k_{358-408}\}, \{k_{409-459}\}]^T \quad (2)$$

The vectors from every subject × side were concatenated to form a 459 × 8488 matrix **K**.

$$\mathbf{K} = \left[\begin{pmatrix} k_1^1 \\ k_2^1 \\ \vdots \\ k_{459}^1 \end{pmatrix} \begin{pmatrix} k_1^2 \\ k_2^2 \\ \vdots \\ k_{459}^2 \end{pmatrix} \cdots \begin{pmatrix} k_1^i \\ k_2^i \\ \vdots \\ k_{459}^i \end{pmatrix} \cdots \begin{pmatrix} k_1^{8488} \\ k_2^{8488} \\ \vdots \\ k_{459}^{8488} \end{pmatrix} \right]. \quad (3)$$

The singular value decomposition of **K** was computed and unit length singular vectors $\{\hat{\boldsymbol{\kappa}}_1, \hat{\boldsymbol{\kappa}}_2, \hat{\boldsymbol{\kappa}}_3, \ldots, \hat{\boldsymbol{\kappa}}_{459}\}$ and singular values $\{\lambda_1, \lambda_2, \lambda_3, \ldots, \lambda_{459}\}$ were preserved. These singular vectors form an optimal orthonormal basis (κ-*basis*) for reconstructing the kinetic gait data and are the "features" referred to in steps 1 and 2 above. The κ-*basis* is optimal in that it maximizes the variance accounted for using the minimum number of features.

From this point, the derivation of the GDI-Kinetic then proceeds exactly as described in Eqs. (3)–(12) by Schwartz and Rozumalski [5].

The resulting GDI-Kinetic is a scaled measure of the distance between a subject's gait and the average gait of a control group. The GDI-Kinetic can be interpreted as follows:

- GDI-Kinetic ≥100 indicates a subject who's kinetics are no further away from the mean control than would be expected of a subject with normal gait. In other words, a GDI-Kinetic of ≥100 indicates normal kinetics.
- Every 10 points that the GDI-Kinetic falls below 100 is one standard deviation further away from the control group mean. For example, a GDI-Kinetic = 86 is 1.4 × S.D. further away from the control group mean than would be expected of a subject with normal gait.

The behavior of the new index for a sub-set of subjects with a diagnosis of Cerebral Palsy (CP) was examined relative to several other established measures of overall gait pathology (GDI, FAQ, and topographical classification as described by Gage [9]).

3. Results

Using 20 gait features accounted for 91% of the variance exhibited in the 8488 strides. This was deemed sufficient for the reconstruction of the kinetic data as it provides ∼23× data compression without introducing significant reconstruction error (Fig. 1).

The GDI and GDI-Kinetic exhibit a statistically significant linear relationship ($p < 0.01$), however strength of this relationship is relatively weak ($r^2 = 0.24$) (Fig. 2).

The GDI-Kinetic is normally distributed among subjects with gait pathology, as well as within separate functional walking levels as measured by the FAQ. The mean GDI-Kinetic values decrease monotonically for subjects in FAQ levels 10 through 6 (Table 1). The average decrement from level 10 to level 7 is 2.4 (SD 1.2).

When examining the mean GDI-Kinetic values for the different CP sub-types, there is the expected decrease from Hemiplegia → Diplegia → Triplegia → Quadriplegia. Interestingly, for Hemiplegia types I–IV, the unaffected limb has a lower GDI-Kinetic score than the affected limb on average (Table 2).

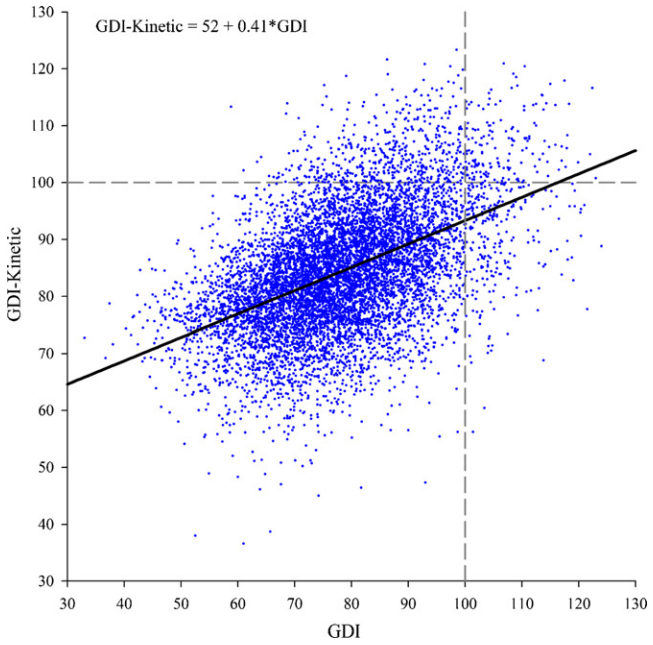

Fig. 2. Scatter plot of the GDI vs. the GDI-Kinetic. The linear relationship (thick black line) shows that the two indexes are related, however, the spread in the data indicates that the indexes measure different aspects of gait pathology. A value of ≥100 indicates absence of pathology (dashed lines).

Table 1
GDI-Kinetic by FAQ level.

FAQ	*N*	Mean GDI-Kinetic
$10^{(9,8,7,6)}$	2041	87.4
$9^{(10,8,7,6)}$	2807	85.0
$8^{(10,9,6)}$	1620	81.6
$7^{(10,9)}$	841	80.5
$6^{(10,9,8)}$	308	79.0

Parentheses indicate FAQ levels that are statistically different from the given level ($p < .01$).

Table 2
GDI-Kinetic by topographic sub-type.

Diagnosis	*N*	Mean GDI-Kinetic
Hemiplegia type I (unaffected side)	52	88.6
Hemiplegia type I (affected side)	52	91.2
Hemiplegia type II (unaffected side)	194	85.8
Hemiplegia type II (affected side)	192	86.6
Hemiplegia type III (unaffected side)	115	83.1
Hemiplegia type III (affected side)	111	85.6
Hemiplegia type IV (unaffected side)	160	77.7
Hemiplegia type IV (affected side)	159	84.2
Diplegia	3536	82.6
Triplegia	785	81.6
Quadriplegia	548	80.4

4. Discussion

The choice of 20 gait features is an arbitrary one. However, with 20 kinetic gait features the patterns were faithfully reconstructed, even when subjects had significant kinetic pathology. The reconstructed data is smoother than the original, while maintaining most of the information related to peaks, ranges, and timing. This is a consequence of the fact that the reduced-order approximation acts as a filter: selectively removing kinetic data that accounts for only a small amount of total variance in the sample. This selectively removed data may be "noise" in the kinetics arising from numerical differentiation, in which case important information is emphasized by the filtering effect. On the other hand, the removed data may reflect rare kinetic patterns, in which case potentially valuable information is lost.

The relatively low correlation coefficient between the GDI and the GDI-Kinetic indicates that for any given level of GDI-Kinetic, there can be a wide variety of kinematic patterns and vice versa; suggesting each index is measuring a different aspect of gait pathology.

Like the GDI, the mean of the GDI-Kinetic decreases monotonically as the FAQ level decreases. There is a larger difference between levels 8, 9, and 10 than between levels 6, 7, and 8. Subjects whose walking ability is classified as level 6 or 7 often require assistive devices when walking in the community. In this study, only subjects who were able to walk without assistive devices during their gait analysis were included. This means that the number of subjects available in the lower FAQ levels was greatly reduced, possibly impacting this result.

An interesting finding relative to diagnostic subtype is that for subjects diagnosed as Hemiplegia types I–IV, the unaffected limb had lower GDI-Kinetic scores than the affected side. This indicates that compensations in the unaffected limb result in greater deviations from normal gait than are seen in the affected limb.

The GDI-Kinetic was developed analogously to the GDI, using gait kinetics instead of kinematics. Although each index provides a global measure of gait pathology, there are distinct differences between them. The GDI-Kinetic thus complements the GDI, giving a more comprehensive measure of gait pathology.

Conflict of interest statement

The authors have no financial or personal relationships with other people or organizations that could influence their work or pose conflicts of interest.

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